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P/2006 HR30 (SIDING SPRING): A LOW-ACTIVITY COMET IN NEAR-EARTH SPACE

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ABSTRACT

The low cometary activity of P/2006 HR30 (Siding Spring) allowed a unique opportunity to study the nucleus of a periodic comet while near perihelion. P/2006 HR30 was originally targeted as a potential extinct comet, and we measured spectral reflectance and dust production using long-slit CCD spectroscopy and wide-field imaging obtained at the Palomar Mountain 200 inch telescope on 2006 August 3 and 4. The dust production $Af\rho = 19.7 \pm 0.4$ cm and mass-loss rate $Q_{\rm dust} = 4.1 \pm 0.1$ kg s^{-1} of the comet were approximately 2 orders of magnitude less than 1P/Halley at similar heliocentric distance. The *VRI* colors derived from the spectral reflectance were compared to Kuiper Belt objects, Centaurs, and other cometary nuclei. We found that the spectrum of P/2006 HR30 was consistent with other comets. However, the outer solar system bodies have a color distribution statistically distinct from cometary nuclei. It is our conjecture that cometary activity, most likely the reaccretion of ejected cometary dust, tends to moderate and mute the visible colors of the surface of cometary nuclei.

Subject headings: comets: general — comets: individual (P/2006 HR30) — Kuiper Belt — minor planets, asteroids — solar system: formation

Online material: color figures

1. INTRODUCTION

It has long been speculated that a significant fraction of Earth-crossing asteroids are possibly dead or dormant comets. The short dynamical lifetimes (30–100 Myr) of near-Earth objects (NEOs) require a constant source of replenishment, which has prompted dynamicists to look toward comets to provide the needed flux (Wetherill 1975; Kresak 1979). Although Yarkovsky thermal forces, when combined with weak mean-motion and secular main-belt resonances, have proven to be an efficient mechanism to transport small main-belt asteroids into Earth-crossing orbits (Bottke et al. 2002), it is still estimated that approximately one-sixth of NEOs are likely of cometary origin (DeMeo & Binzel 2006). Comets and asteroids represent two end-members in composition, with rocky asteroids forming between Mars and Jupiter and icy/dusty objects accreting beyond the orbit of Jupiter. It was the formation of the outer planets that led to the dispersal of the primordial ring of comets, flinging the inner edge of the Kuiper Belt into the Oort Cloud. It is these distant reserves, the Kuiper Belt and Oort Cloud, that resupply the comets that cross the inner solar system.

The dynamics of comets can be understood using the Tisserand parameter T, a quasi constant in the restricted three-body problem (Weissman et al. 2002):

$$T = \frac{a_{\rm J}}{a} + 2\left[\frac{a}{a_{\rm J}}(1-e^2)\right]^{1/2}\cos i, \qquad (1)$$

where $a_{\rm J}$ is Jupiter's semimajor axis and a, e, and i are the object's semimajor axis, eccentricity, and inclination, respectively. With few exceptions, most notably the Jupiter Trojans, all main-belt asteroids have $T > 3$ while comets exhibit $T < 3$, reflecting the fact that the orbits of comets are evolving inward from the outer solar system. Discovered on 2006 April 20 by R. McNaught and G. Garrard at Siding Spring Observatory, our target was announced as a minor planet and designated 2006 HR30 (Bambery et al. 2006). With $T = 1.79$ (a, e, i = 7.81 AU, 0.84, 31.9°), we targeted the asteroid as an extinct comet candidate (ECC). Our observations and those by other independent observers revealed cometary activity, and the object was quickly reclassified as a comet (Lowry et al. 2006).

With the ongoing NEO discovery surveys, the reclassification of asteroids to comets occurs with increasing frequency; 161P/Siding Spring (2004 TU12) was discovered as an NEO and reclassified with the detection of coma (Mallia et al. 2004). This object was the subject of extensive study by the collective teams of Fernández et al. (2006) and Campins et al. (2006), who measured spectral reflectance and thermal emission of the nucleus, revealing a large 12 km diameter and low geometric V albedo of 0.034. Thermal observations of ECCs (Fernández et al. 2001; Harris et al. 2001) provide constraints on the relative fraction of extinct comets in the NEO population. This is important for understanding the hazard to the Earth from comet and asteroid collisions.

2. OBSERVATIONS AND DATA REDUCTION

Moderate resolution CCD spectrograms of P/2006 HR30 were obtained at the Palomar 200 inch (P200) using the Cassegrain-mounted Double Spectrometer (DBSP; Oke & Gunn 1982) on the nights of 2006 August 3 and 4. The observational circumstances are listed in Table 1, with heliocentric distance r, geocentric distance Δ, and solar phase angle α computed by the Jet Propulsion Laboratory HORIZONS ephemeris service. Within the DBSP, the sky and object are imaged on the slit before being divided by a dichroic filter into red and blue beams, which are then dispersed and reimaged with individual grating and camera setups. All observations were performed through a 4″ spectroscopic slit with the tailpiece rotated to match the parallactic angle. In addition to the comet, we collected spectral exposures of the solar analog stars 16 Cyg B, HD 144873, SA 110−361, SA 112−1333, SA 113−276, and SA 114−654 at air masses that bracketed the comet. Both nights were clear and photometric. Our reductions proceeded in the standard manner, with our methods discussed in greater detail in Hicks & Buratti (2004). Ex-

TABLE 1
P/2006 HR30 (Siding Spring) Observational Circumstances

UT Date	r (AU)	Δ (AU)	α (deg)	⟨Seeing⟩ (arcsec)	Int. Time (s)	Data Type
2006 Aug 03	2.32	1.47	16.9	1.4	2 × 180, 1 × 300	DBSP
2006 Aug 04	2.31	1.45	16.7	0.8	4 × 300	DBSP
	...	...	...	...	26 × 10	LFC

posures from the two spectral channels were separately analyzed and combined into continuous spectra spanning 0.38–0.96 μm with a dispersion of 2.14 Å channel^{-1} in the blue camera and 4.88 Å channel^{-1} in the red.

Imaging data was taken with the P200 Large Format Camera (LFC) on the night of 2006 August 4. The LFC is a mosaic of six 2048 × 4096 15 μm pixel thinned, back-side illuminated CCDs with a field diameter of 24′ mounted at prime focus. Only one CCD was read out, and it was binned 2 × 2 giving a plate scale of 0.36″ pixel^{-1}. Twenty-six sequential 10 s Bessel R (0.63 μm) exposures of the comet were collected. The reductions were performed within the IRAF environment (Tody 1986) with a photometric aperture of 3.6″ in radius and with a sky annulus from 3.6″ to 7.2″. Landolt standard stars (Landolt 1992) PG 0231+051A, PG 0231+051B, PG 0231+051C, PG 0231+051D, SA 113−189, SA 113−195, and SA 113−307 were observed to measure zero-point offset and air-mass extinction correction. The formal calibration error was less than 0.01 mag. On the night of August 3, the cometary nature of 2006 HR30 was noted first in our spectral exposures as a faint fog extending beyond the slit jaws. After DBSP spectroscopy, we switched to LFC imaging, which confirmed the coma but saturated the inner pixels. Therefore, the August 3 imaging data was not included in our analysis.

3. ANALYSIS AND DISCUSSION

Figure 1 shows the surface brightness profile (SBP) of P/2006 HR30 and the associated stellar SBP as measured from a composite of field stars. The flux from the nucleus of P/2006 HR30 dominated the inner coma, with the majority of the dust

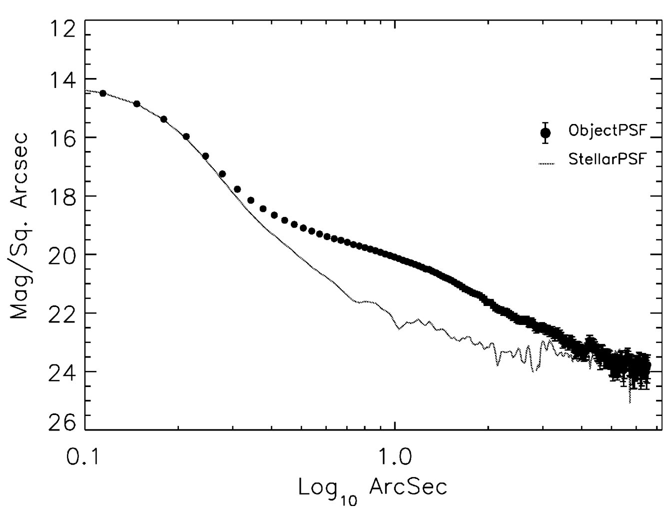

Fig. 1.—Azimuthally averaged surface brightness profile of P/2006 HR30 and composite stellar brightness profile from 2006 August 4 R-band imaging. Flux from the coma dominates at projected distances greater than 2″ and extends to approximately 25″. [*See the electronic edition of the Journal for a color version of this figure.*]

confined in a northerly oriented jet. The mean observed R magnitude of the nucleus plus coma was measured at $R_{tot} = 15.59 \pm 0.01$. To estimate the size of the nucleus and rate of dust production, it was necessary to model the coma contamination. With uniform steady state outflow, the column density of cometary dust coma falls off as ρ^{-1}, where ρ is the projected distance from the nucleus. This is valid in the inner coma where effects from solar wind acceleration and fading cometary grains can be ignored. We developed a model that fitted a constant sky background and a ρ^{-1} coma component for each azimuth from the photometric center of the comet to the edge of the image, extrapolating to the ρ^{-1} component to the photocenter of the image at distances less than the seeing disk, as illustrated in Figure 2. The computed coma contamination was ~8%, and photometry of the coma-subtracted images gave a mean observed nuclear magnitude $R_{nuc} = 15.69 \pm 0.01$. Assuming a phase parameter $G = 0.0$ and geometric albedo $p_R = 0.05$, we measured the absolute magnitude $H_R = 11.99 \pm 0.01$, corresponding to a diameter $D \sim 22$ km. Dust production rates were estimated using the well-known $Af\rho$ formalism (A'Hearn et al. 1984):

$$Af\rho(\alpha) = (4r^2\Delta^2/\rho)(F_{dust}/F_{solar}), \tag{2}$$

where A is the wavelength-dependent albedo of the dust grains, f is the ratio of the cross section of the dust grains to the total field of view, ρ is the projected radius of the photometric aperture in centimeters, α is the solar phase angle, r is the heliocentric distance in AU, and Δ is geocentric distance in centimeters. The mean $Af\rho = 19.7 \pm 0.4$ cm was 2 orders of magnitude less than 1P/Halley at a similar heliocentric distance (Schleicher et al. 1998). Dust production of 35 comets with known nuclear diameters (Schleicher et al. 1998, 1997; A'Hearn et al. 1995; Hicks 1997; Cochran & Barker 1999; Fink et al. 1999; Schleicher & Osip 2002) were compiled and used to compute normalized activity:

$$\Gamma = \overline{Af\rho}/\sigma, \tag{3}$$

where $Af\rho$ is reduced to 1 AU assuming the $r^{-2.15}$ dependence measured for 1P/Halley (Schleicher et al. 1998) and normalized by the geometric cross section of the nucleus σ. This activity index is only valid at heliocentric distances less than ~4 AU, where dust production is dominated by the sublimation of water. As illustrated in Figure 3, P/2006 HR30 has the lowest activity index of the well-characterized comets.

The value of $Af\rho$ can be used to estimate mass-loss rate Q_{dust} (Bauer et al. 2003) with the expression

$$Q_{dust} = Af\rho(0°)(\tfrac{4}{3}\pi a^3 v_{ej}\sigma)/\pi a^2 p. \tag{4}$$

We assumed a mean dust grain radius $a = 1$ μm, dust albedo $p = 0.04$, grain density $\sigma = 1$ g cm^{-3}, ejection velocity consistent

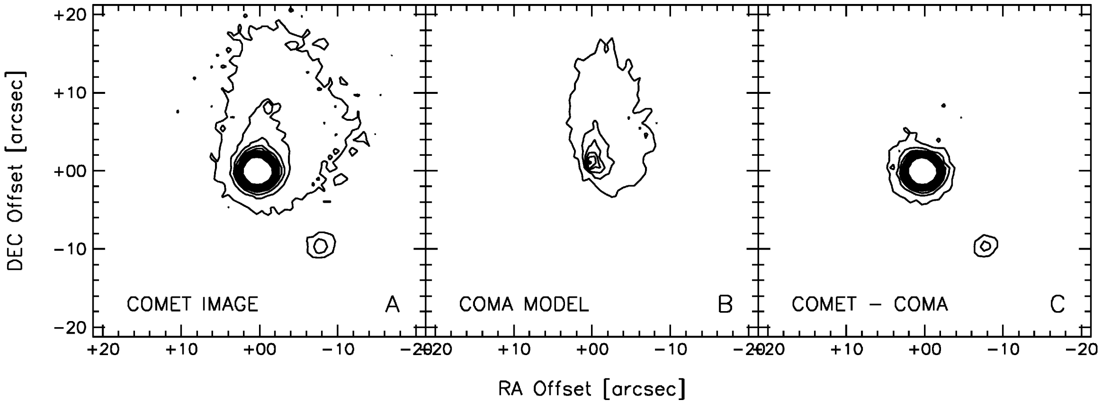

FIG. 2.—P/2006 HR30 raw comet image and coma model. For the 2006 August 4 Palomar 200 inch LFC data, a $1/\rho$ coma model was fit at each azimuth of every image, allowing us to subtract the coma cleanly and measure the R-band fluxes from the nucleus and coma separately. The contours are at 100 DN increments.

with water sublimation $v_{ej} = 600r^{-1/2}$ m s^{-1} = 500 m s^{-1}, and a phase coefficient for the cometary dust of 0.015 mag deg^{-1}, and we estimated a mean mass-loss rate $Q_{dust} = 4.1 \pm 0.1$ kg s^{-1}. As a consistency check for dust production, we used the SBP technique as described by Meech & Weaver (1996) and Bauer et al. (2003), computing upper limits to $Af\rho$ and Q_{dust} from the maximum signal attributable to the coma. We found upper limits using this technique of $Af\rho \sim 8$ cm, in reasonable agreement with our coma model.

The spectral reflectance of P/2006 HR30 is consistent with the other cometary nuclei (Lamy et al. 2004), as shown in Figure 4. It is not clear if the slight difference between the August 3 and August 4 spectra is spurious or rotational variability. The same solar analog stars were used for both nights. Assuming Bessel *BVRI* effective wavelengths (0.44, 0.55, 0.63, 0.90 μm), we estimated approximate solar-subtracted colors of $B - V = 0.172 \pm 0.016$ mag, $V - R = 0.098 \pm 0.008$ mag, and $V - I = 0.316 \pm 0.015$ mag. The formal error in our color measurement is a lower limit; there is perhaps 10% contamination in our spectrum by dust. This is likely a second-order effect; cometary dust is typically neutral to only modestly red (Hicks 1997). In order to compare P/2006 HR30 with main-belt asteroids and outer solar system bodies (OSSBs), we first determined the approximate colors of 1341 SMASS II asteroid spectra as archived in the PDS (Bus & Binzel 2002[1]). The left-hand panel of Figure 4 presents *VRI* colors of P/2006 HR30 as well as S-, C-, and D-type main-belt asteroids. Also plotted are Centaurs, Plutinos (Kuiper Belt objects [KBOs] in a protected resonance with Neptune), "classical" KBOs (cubewanos: KBOs whose orbits are not Neptune-crossing), and cometary nuclei (Tegler et al. 2007). All photometry has $V - R$ error ≤0.1 mag. The cometary nuclei, including P/2006 HR30, have well-constrained colors similar to D-type asteroids. This is in contrast to the KBOs and Centaurs, which show much greater variability. To the eye, the cubewanos exhibit the greatest *VRI* variability while the Plutinos and Centaurs are indistinguishable.

To quantify these correlations, we applied the Kolmogorov-Smirnov (K-S) statistic to our *VRI* colors. The K-S test (Press et al. 1988, p. 635), a metric that ranges from 0 to 1, provides a useful approximation of the probability that two populations, both functions of a single independent variable, are drawn from the same distribution. We computed the K-S statistic for the $V - R$, $R - I$, and $V - I$ colors separately using a number of population pairs. Our results are summarized in Table 2. What was apparent by casual examination was confirmed numerically: although dynamically linked with Centaurs and KBOs, the visible colors of cometary nuclei are quite distinct from other outer solar system bodies, with a very low probability that the populations are derived from the same color distri-

[1] See also the NASA Planetary Data System at http://starbrite.jpl.nasa.gov/pds-explorer/index.jsp?selection=dsid; data set EAR-A-I0028-4-SBN0001/SMASSII-V1.0.

TABLE 2
K-S TEST APPLIED TO OSSB COLOR DISTRIBUTIONS

Populations Tested				Probability		
Population 1	No.	Population 2	No.	$V-R$	$R-I$	$V-I$
Comets	9	Centaurs	24	0.043	0.076	0.128
	9	Cubewanos	24	0.006	0.001	0.043
	9	Plutinos	19	0.043	0.007	0.043
	9	All KBOs	43	0.009	0.001	0.046
Centaurs	24	Cubewanos	24	0.259	0.259	0.259
	24	Plutinos	19	0.758	0.592	0.337
	24	All KBOs	43	0.341	0.317	0.221
Plutinos	19	Cubewanos	24	0.803	0.825	0.664

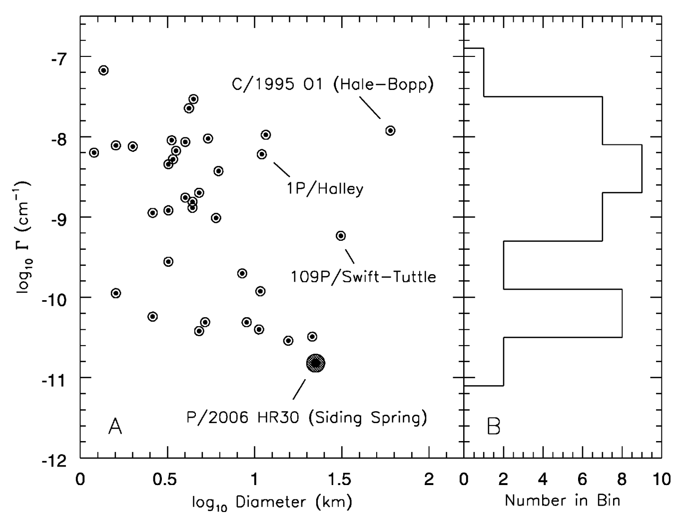

FIG. 3.—Normalized cometary dust production. The activity index Γ of P/2006 HR30 and 35 comets with known nuclear diameters are plotted in (*a*). The histogram in (*b*) suggests that this distribution may be bimodal. [*See the electronic edition of the Journal for a color version of this figure*.]

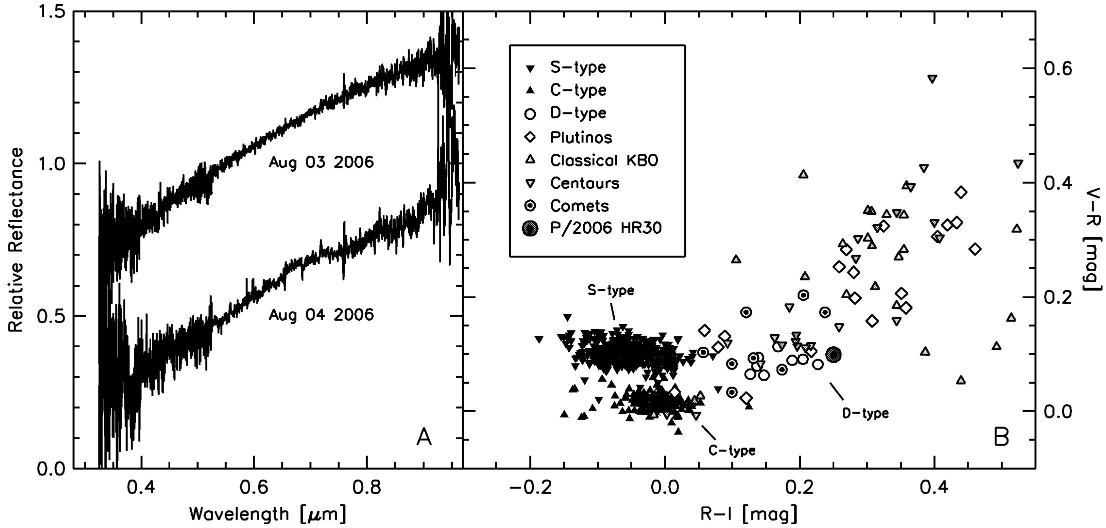

FIG. 4.—Low-resolution spectra and colors of P/2006 HR30. The spectra in (*a*) are normalized at 0.55 μm, and the August 4 data is offset downward by 0.5 for clarity. In (*b*), the solar-subtracted colors of the major main-belt asteroid classes (S-, C-, D-type) and outer solar system objects, including Kuiper Belt objects, Centaurs, and cometary nuclei, are plotted. Cometary nuclei exhibit a color distribution quite distinct from KBOs. [*See the electronic edition of the Journal for a color version of this figure*.]

butions. It is necessary to reconcile this fact with models of cometary formation and evolution. The K-S statistic suggests that Centaurs have colors more similar to Plutinos than to classical KBOs; however, the K-S test did not significantly distinguish Plutinos from classical KBOs.

We summarize our results:

1. Discovered as an asteroid in the inner solar system, P/2006 HR30 was reclassified after the detection of faint coma. Model fits suggest extremely low dust production, $Af\rho = 19.7 \pm 0.4$ cm, given its large diameter, $D \sim 22$ km.
2. Long-slit CCD spectroscopy over two nights yielded a moderately red featureless spectrum similar to other cometary nuclei, with effective *VRI* colors consistent with D-type asteroids.
3. Although comets have been shown to be dynamically derived from OSSBs, the application of the K-S test very strongly suggests that they have color distributions distinct from Centaurs and KBOs. It is our conjecture that cometary activity effectively moderates and mutes the visible colors of comet surfaces.

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